11th Conference on Learning Factories, CLF2021

Development of an intelligent warehouse and autonomously controlled intralogistics scenario to investigate the mastering of short-term turbulences at Werk150

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Abstract

Manufacturing companies are confronted with external (e.g. short-term change of product configuration by the customer) and internal (e.g. production process deviations) turbulences which are affecting the performance of production. Predefined, centrally controlled logistics processes are limiting the possibilities of production to initiate countermeasures to react in an optimized way to these turbulences. The autonomous control of intralogistics offers a great potential to cope with these turbulences by using the respective flexibility corridors of production systems and applying intelligent logistic objects with decentralized decision and process execution capabilities to maintain a target-optimized production. A method for AI-based storage-location- and material-handling-optimization to achieve performance-optimized intralogistics system through continuous monitoring of performance-relevant parameters and influencing factors by using AI (e.g. for pattern recognition) has been developed. To provide the basis to investigate and demonstrate the potentials of autonomously controlled intralogistics in connection with turbulences of production and in combination with AI, an intelligent warehouse involving an indoor localization system, smart bins, manual, semi-automated/collaborative and autonomous transport systems has been developed and implemented at Werk150, the factory on campus of ESB Business School (Reutlingen University). This scenario, which has been integrated into graduate training modules, allows the analysis and demonstration of different measures of intralogistics to cope with turbulences in production involving amongst others storage and material provision processes. The target fulfilment of the applied intralogistics measures to master arising turbulences is assessed based on the overall performance of production considering lead times and adherence to delivery dates. By applying artificial intelligence (AI) algorithms the intelligent logistical objects (smart bin, transport systems, etc.) as well as the entire logistics system should be enabled to improve their decision and process execution capabilities to master short-term turbulences in the production system autonomously.

Peer Review statement: Peer-review under responsibility of the scientific committee of the 11th Conference on Learning Factories 2021.

Keywords: Turbulences; Learning Factory; Smart Warehouse; Smart Storage; Autonomous Control; Intralogistics; Flexibility;

1. Introduction

Companies are increasingly confronted with the challenge of a more turbulent market and customer environment [1,2]. This requires a responsive and target-oriented adaptation of production and logistics processes to the changing framework conditions [2,3]. Purely deterministic planning does not provide optimal solutions in turbulent systems and thus results in lower overall system performance. Furthermore, the potential of flexible production systems cannot be fully exploited through the use of conventional, hierarchical control due to the arising complexity of the system [3,4]. Autonomous control enables to deal with increasing complexity and dynamics and thus increases the flexibility and robustness of production and intralogistics systems based on decentralized information processing, decision-making and execution at the system element level [5]. For example, the autonomous control of intralogistics processes offers the potential to adjust material provisioning when production-

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related turbulences (e.g. machine failure, delay of a previous order at a production resource, wrong/defect parts provided) occur. In such a case, the resource allocation of production orders to machines can be changed flexibly and at short notice (by using the machine and operation flexibility corridors) in line with the autonomously controlled material provision process to meet defined production goals.

To investigate and demonstrate the potentials of autonomously controlled intralogistics in connection with turbulences in flexible production systems, an analysis of different types of flexibility, turbulences and potential measures of autonomously controlled intralogistics systems has been conducted. The identified measures of autonomously controlled intralogistics systems should support the use of the available types of flexibility of flexible production systems to cope with short-term turbulences and to maintain short lead times and high adherence to delivery dates. Based on these investigations, an intelligent warehouse and autonomously controlled intralogistics scenario as well as suitable training modules for the defined learning goals for graduate students, aiming to transfer the gained findings into university education, have been developed for further investigation and demonstration of the mastering of short-term turbulences at Werk150.

2. Types of flexibility and turbulences in flexible production systems

The study of the flexibility types of flexible production systems is central to the investigation of the potentials of autonomously controlled intralogistics logistics, as they provide the framework in which the negative effects of turbulences on production goals can be limited through decentralized information processing, decision-making, and process execution of autonomously controlled intralogistics systems.

2.1. Types of flexibility of production systems

Flexible production systems allow the production of different products without having to physically change the structure of the system, as they have built-in flexibility with defined boundaries [6]. Following *ElMaraghy* [7] at least 10 types of production system flexibilities can be distinguished, which allow production systems amongst others to deal with uncertainties with only minor losses in terms of time, effort, costs or performance. However, the types of flexibility cannot always be differentiated from one another with complete clarity and are in some cases linked with one another. The result of the conducted literature review is summarized in Table 1.

Table 1. Types of flexibility of production systems.

Type of production flexibility	Description	Flexibility parameter
Machine flexibility	Various operations can be performed without set-up changes and capability of a machine to perform different operations [7,8]	Number of operations
Material handling flexibility	Number of used or possible paths between all machines and ability of the material handling system to transport different work pieces effectively between different workstations [7,8]	Number of possible transport paths
Operation flexibility	Ability to produce a defined set of products by using different machines, materials, operations and sequence of operations based on different processing plans to produce a part [7,9,10]	Number of processing plans
Process flexibility	A defined set of part types can be produced without major set-up changes and ability to alter between the production of different parts or products [7,8]	Number of parts/products that can be produced
Product flexibility	Ease (time and cost) to introduce products into an existing product mix which enables the production system to produce various part types using the same equipment [7,9,10]	Ease (time and cost) to introduce products
Routing flexibility	Number of feasible routes to manufacture all part types or a certain number of part types under the condition that operations can be performed on several machines [7,11,12]	Number of feasible routes for manufacturing
Volume flexibility	Ability to vary production volumes of different products within production capacity to be able to deal with fluctuations in demand and at the same time remain profitable [7,9,10]	Production volume
Expansion flexibility	Ease (effort and cost) to expand capacity and/or capability by a physical change of the production system [7,8]	Ease (effort and cost) to expand capacity/capability
Control program flexibility	Ability of a the production system to run virtually uninterrupted and unattended (e.g. during night or extra shifts) based on intelligent plant infrastructure and control systems [7,8]	Degree of autonomy
Production flexibility	Number of part types which can be produced within an existing production system without major capital investments [7,8]	Number of part types

In order to tap these flexibility potentials, the interaction of production and intralogistics is of central importance. This interaction is necessary because an essential prerequisite for the flexible execution of production processes, beside the provision of the required information, is an adapted and flexible provision of the required materials via the respective intralogistics transport systems. For example, in order to utilize the potential of "operation flexibility" for the production of a production order via an alternative processing plan in the event of turbulence, a (short-term) adjustment of the material flow by the intralogistics system is required. The need to maintain these types of flexibility in the production system is primarily due to the need to deal with unforeseen events or turbulence originating outside and inside the company. These turbulences are analyzed in more detail below with regard to their effects on the control of intralogistics processes.

2.2. Turbulences and measures of autonomously controlled intralogistics systems

Turbulences can be differentiated into internal and external turbulences with regard to their places of origin. Thus, internal turbulences originate in unforeseen changes within the company, while external turbulences arise due to reasons external to the company [13]. The planning processes of companies are particularly confronted with medium-term external (e.g. change in demand quantities) and internal (e.g. increasing number of variants) turbulences [13,14]. The control of production and intralogistics processes is mainly faced with short-term turbulences in terms of unexpected deviations from the plan, such as machine breakdowns or process delays, which endanger the adherence to the plan and its related objectives [15].

The essential requirements for logistics, which must also be adhered to in the event of turbulence, are described with the seven R's of providing the right quantity of the right product at the right place at the right time in the right condition at the right price with the right information [16]. These requirements also apply to the execution of internal material flows in companies, which can be fulfilled by intralogistics systems in particular through the selection of a suitable transport system to provide the materials required for production in the right condition at the respective place of demand in the right quantity at the right time with the right information. Autonomously controlled intralogistics thus offers a lever for coping with turbulence in the production system, in particular by changing or selecting a suitable transport system fulfilling cost and performance goals to satisfy changing material requirements (material type, quantity, source and sink). Triggers for control-relevant turbulence can be found in particular at the supply, production and customer level. The analysis was carried out under the premise that the short-term turbulences affect the release of the production orders. In the course of order release, the prerequisites for order execution in terms of material, capacity and operating resources are checked using the existing flexibility of the production system [17]. These production orders with defined production resource, planned start date and required material form the basis for the autonomously controlled execution of the intralogistics processes such as the provision of the required materials at the production resources as well as for the required transports between the respective work stations.

Table 2 provides an overview of the main turbulences identified from the literature and discussions with experts, measures of flexible production and autonomously controlled intralogistics to cope with these turbulences as well as the types of flexibility exploited by the application of autonomously controlled intralogistics [13–15]. The analysis of the turbulences affecting the control of production and intralogistics processes and the respective measures of flexible production and autonomously controlled intralogistics showed that the application of autonomously controlled intralogistics is supporting the exploitation of the flexibility types of operation, routing and material handling flexibility to cope with turbulences arising at the production and customer level. Thus, in the event of turbulence in the production system or from the customer level, the use of autonomous control of the intralogistics processes can unlock the flexibility potential of operation flexibility (production of products based on different processing plans) by providing the required material at an alternative production resource at short notice. The same applies to the unlocking of the potential of routing flexibility for the production of products using alternative feasible routes to manufacture the products in case of turbulences. In the event of turbulence at the intralogistics system level (e.g. failure or delay of a vehicle), the flexibility potential of material handling flexibility can be tapped by the autonomous control of intralogistics based on a goal-oriented transport system and route selection as well as process execution.

Table 2. Control-related turbulences.

Level	Sublevel	Turbulence	Measure of flexible production	Measure of autonomously controlled intralogistics	Type of flexibility exploited by autonomously controlled intralogistics
Supply		Unexpected material deviation (wrong specification)	Rescheduling of the production order in production planning and control before production order release	No action required, as the effect of turbulence occurs before the production order is released	-
		Delivery date deviation			
		Quantity deviation in delivery			
Production	Manufacturing system	Resource breakdown: machine/employee	Allocation of the production order to an alternative production resource	Provision of the required materials to changed material sink (production resource)	Operation flexibility Routing flexibility
		Target vs. actual time deviation at resource/workstation (delay)			
		Missing part at resource/workstation (Wrong or faulty part)	Request of spare part / missing part	Triggering of a (rush) transport order (incl. return delivery of wrong or faulty part) and allocation to transport system	Material handling flexibility
		Excess supply (too much material)	Request of return delivery	Return delivery of surplus material	Material handling flexibility
	Intralogistics system	Resource failure: transport system (human or machine)	Not involved	Material provision with alternative transport system	Material handling flexibility
		Target vs. actual time deviation (transport time increases)	Not involved	Prioritization of material supply to material sinks which are threatened by immediate standstill due to material shortage	
Customer		End product change (changed configuration)	Changed production order goes through order release (check: material, capacity, operating resources) and is allocated to production resource	Material provision of the changed material type and quantity to the corresponding material sink	Operation flexibility Routing flexibility
		Change of the requirement date		Material provision with changed target date	
		Quantity change of a customer order		Material provision with changed material quantity	

The theoretical investigations above indicated that the application of autonomous control of intralogistics systems offers a great potential to cope with arising short-term turbulences, as this allows the existing flexibility potential of flexible production systems to be tapped in a targeted manner. For a practice-oriented investigation and demonstration of these potentials, an intelligent warehouse and autonomously controlled intralogistics scenario has been developed and implemented at Werk150.

3. Intelligent warehouse and autonomously controlled intralogistics scenario at Werk150

The scenario realized at Werk150 covers major types of flexibility to provide the basis for an investigation of the potentials of autonomous control using the flexibility potentials of flexible production systems to deal with turbulences in a target-optimized way. It incorporates the autonomously controlled supply of material by means of manual, semi-automated/collaborative and fully automated transport systems from the (intelligent) warehouse into the production system, which is subject to turbulence (see Fig. 1).

Fig. 1. Intelligent warehouse and autonomously controlled intralogistics scenario.

To integrate the intelligent warehouse and autonomously controlled intralogistics scenario into university teaching, first training modules for graduate students were developed and implemented at Werk150. The teaching methods used are based on the four-step method according to *Riffelmacher* [14]. The four steps are: Teaching of theoretical content via a lecture, demonstration by the lecturer in the learning factory, application of the learning content by the participants using an example and finally independent application in the learning factory by the participants. For first tests, the training modules described below have been integrated into a graduate lecture.

3.1. Training module 1: Autonomous control of intralogistics to master short-term turbulences

Building on the theoretical input from the lecture, this training module aims to teach the potential of autonomous control of intralogistics systems to cope with short-term turbulence by using the flexibility of the production system in an application-oriented manner. Within first trainings with students, turbulences such as resource failures (e.g. collaborative robot, 3d printer) and missing/wrong/defect parts or materials at workstation were fed into the production system of Werk150 by the instructor. In case of resource failures, the use of the flexibility types of operation and routing flexibility have been demonstrated to the students. Therefore, the autonomous control system at Werk150 enables and initiates the provision of the required materials at the alternative resource based on an alternative processing plan. The students can then experience live in the production system how to react to the resource failure in a target-optimized way using autonomously controlled intralogistics. For missing/wrong/defect parts or materials, the use of the flexibility type of material handling flexibility to identify a suitable transport system for the transport of the required parts or materials to the respective workstation can be demonstrated. In context with the autonomous control of intralogistics, the execution of this transport order is then inquired from all available transport systems (automated guided vehicles, collaborative tugger train and manual hand trolley) or their software agents, and a decision is made decentrally with regard to the target dimensions of lead-time and adherence to schedules. The transport systems are aiming at minimizing costs and maximizing their performance with a variable prioritization when they are bidding on the transport orders that have to be fulfilled [18]. This shows students integrated into the production of Werk150 the potential for improved adaptability of intralogistics systems to changing conditions within the material handling flexibility. The result of this decision-making process can be visualized for the students in corresponding dashboards of the autonomous control system framework of Werk150. The generated information and target fulfilment of the executed changes will also be incorporated into the target-optimized AI-based decision-making of the intelligent logistic objects and systems (transport systems, intelligent warehouse, etc.) for improved autonomous mastering of short-term turbulences in the production system.

3.2. Training module 2: Intelligent warehouse

In conjunction with a developed training module on the subject area of AI and intelligent warehouses, the warehouse of Werk150 has been transformed into a first level of an intelligent warehouse by using smart technologies such as intelligent bins and an indoor localization system to enable an AI-supported analysis, execution and optimization of storage and material provision processes. All bins in the warehouse are equipped with e-Ink displays, which are used to display dynamic information to the employee directly on the bin (e.g. current quantity, destination of the bin). In addition, the use of these displays instead of paper labels on the bin supports the use of the bins in bin cycles with variable part contents. Besides these bins with a rather low degree of intelligence, intelligent bins with identification, data storage, information processing and communication capabilities are used. To detect the amount of parts in the bin, an AI-based object recognition method has been implemented at the intelligent bin. The intelligent bin also detects environmental influences (e.g. light, vibration) via sensors and can be localized by the indoor localization system used at Werk150. As a first step, a demonstrator for AI-assisted storage space optimization using indoor localization technology is currently under development. This demonstrator will be used to show students the potential of using AI in the warehouse area after a theoretical introduction to the topic. In this training module, the students should independently learn about the potentials of an AI-based storage-location- and material-handling-optimization in practical application. Based on an initial scenario with performance deficits (long walking distances, very high or low bin positions etc.) students can independently develop solutions for improving storage location allocation and material handling using AI-based evaluations and optimizations. Therefore, a method for AI-based storage-location- and material-handling-optimization will be developed to achieve a performance-optimized intralogistics system through continuous monitoring of performance-relevant parameters and influencing factors by using AI (e.g. for pattern recognition). For the analysis of material provision processes, heatmaps can be generated based on different input-information. The information originating from material planning in combination with position information of the executed processes, which shows the duration of stay of the logistics employees in certain warehouse areas, can be used to dynamically optimize the arrangement of bins in the warehouse. The objective here is to minimize the walking distances of humans or the travel distances of transport systems for common order constellations. Information coming from the control processes to master short-term turbulences allows a retrospective analysis of turbulences and their effect on the warehouse (central/decentralized locations, storage place of the bins, material-handling times) as well as the derivation of possible optimizations of the overall production system of Werk150.

4. Conclusion

The scenario and training modules developed and realized at Werk150 provide the preconditions for the investigation and demonstration of different measures of intralogistics to cope with turbulences in production by using intralogistics-related corridors of flexible production systems. The next steps will involve the execution of numerous production runs with intentionally introduced as well as randomly arising turbulences in the production system. In this way, a sound database shall be generated for the training of the AI applications as well as for the further development of a method for the autonomous control of intralogistics under consideration of turbulences. To support a further transfer of the gained findings and results, first into university education via the learning factory, additional training modules will be created and further developed for graduate students. For the transfer of the findings to small and medium-sized enterprises, accompanying information materials and industry seminars will be developed and used in existing project initiatives in the context of digital twins and AI.

Acknowledgements

Research supporting these results have been funded by the EFRE Program Baden-Württemberg 2014-2020, Project: ZAFH Intralogistik and the Steinbeis Innovationszentrum Transferplattform BW Industrie 4.0.

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